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2011 MARS SCIENCE LABORATORY LAUNCH PERIOD DESIGN

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The Mars Science Laboratory mission, set to launch in the fall of 2011, has the primary objective of landing the most advanced rover to date to the surface of Mars to assess whether Mars ever was, or still is today, able to sustain carbon-based life. Arriving at Mars in August 2012, the Mars Science Laboratory will also demonstrate the ability to deliver large payloads to the surface of Mars, land more accurately (than previous missions) in a 20-km by 25-km ellipse, and traverse up to 20 km. Following guided entry and parachute deployment, the spacecraft will descend on a parachute and a Powered Descent Vehicle to safely land the rover on the surface of Mars. The launch/arrival strategy is driven by several key requirements, which include: launch vehicle capability, atmosphere-relative entry speed, communications coverage during Entry, Descent and Landing, latitude accessibility, and dust storm season avoidance. Notable among these requirements is maintaining a telecommunications link from atmospheric entry to landing plus one minute, via a Direct-To-Earth X-band link and via orbital assets using an UHF link, to ensure that any failure during Entry, Descent and Landing can be reconstructed in case of a mission anomaly. Due to concerns related to the lifetime of the relay orbiters, two additional launch/arrival strategies have been developed to improve Entry, Descent, and Landing communications. This paper discusses the final launch/arrival strategy selected prior to the launch period down-selection that is scheduled to occur in August 2011. It is also important to note that this paper is an update to Ref. 1 in that it includes two new Type 1 launch periods and drops the Type 2 launch period that is no longer considered.

INTRODUCTION

The overall scientific goal of the Mars Science Laboratory (MSL) mission is to determine the planet's habitability and continue the search for evidence of past or present life on Mars using the most advanced suite of instruments for scientific studies ever sent to the Red Planet. Besides assessing the biological potential of the landing site and characterizing its geology, MSL will also take measurements of the surface radiation. The 900-kg MSL rover is five times as massive as the Mars Exploration Rovers (MER) launched in 2003 and is the first interplanetary mission to use guided entry to compensate for trajectory errors and atmospheric and aerodynamic dispersions in order to reduce the size of the landing error ellipse from 60 km (MER) to less than 25 km. The MSL rover pioneers the next generation of robotic systems capable of delivering the largest payloads to the surface of Mars.[1]

The MSL spacecraft will be launched on an Atlas V 541 Expendable Evolved Launch Vehicle (EELV) from the Eastern Test Range at Cape Canaveral Air Force Station (CCAFS) in Florida during the 2011

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Earth to Mars opportunity with launch dates ranging from late November through mid December and will arrive at Mars in early to mid August 2012. The exact arrival date depends on the launch day and landing site selected.[2]

The MSL flight system consists of an Earth-Mars cruise spacecraft, an atmospheric Entry, Descent, and Landing (EDL) system, and a mobile science rover. The primary data return paths during EDL are via an X-band direct-to-Earth communications link through the Deep Space Network (DSN) and an Ultra High Frequency (UHF) link to existing Mars network orbiting assets, which include Mars Reconnaissance Orbiter (MRO) and Mars Odyssey (ODY).[3] The entry vehicle is comprised of a 4.5-m heatshield, backshell, descent stage (including the skycrane), and the rover. For comparison purposes, Figure 1 shows the aeroshell used for the 1975 Viking landers, the 1996 Mars Pathfinder (MPF) and the 2003 Mars Exploration Rovers, and the 2011 Mars Science Laboratory.

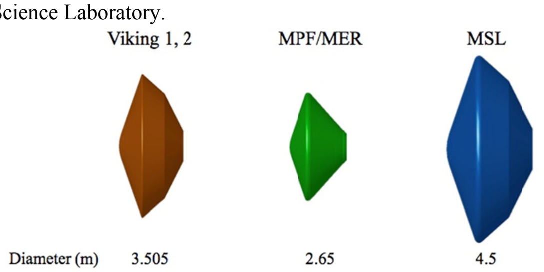

Figure 1. Aeroshell Heritage: Viking, MPF, MER, and MSL

Figure 2 shows exploded views of the Mars Pathfinder, the Mars Exploration Rover, and Mars Science Laboratory flight systems.

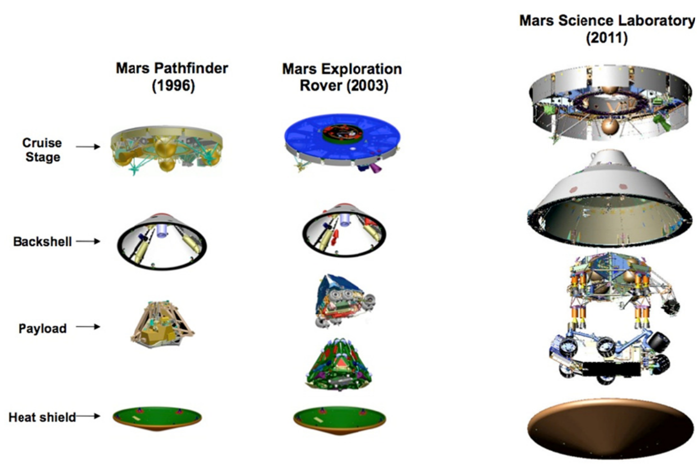

Figure 2. Flight System Exploded Views: Viking, MPF, MER, and MSL

While the organization and general content of this paper resemble that of Ref. 1, and indeed the formerly known Type 1 launch period (now referred to as the Type 1A launch period) is still part of the baseline, the Type 2 launch period has been eliminated and two additional Type 1 launch periods have been added to the launch/arrival strategy. This paper also includes significant updates to the launch window duration, separation attitude, initial acquisition, and EDL coverage via orbital assets.

The MSL rover carries an ~80-kg instrument package composed of a suite of 10 scientific instruments that cover the areas of remote sensing (Mastcam and ChemCam), in-situ (MAHLI and APXS), analytical (CheMin and SAM), and environmental (RAD, MARDI, DAN, and REMS). The rover is powered by a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) that has more than a 14-year lifetime and generates ~110 W of electrical power at the start of the prime mission. Figure 3 shows the location of the different instruments on the MSL rover.

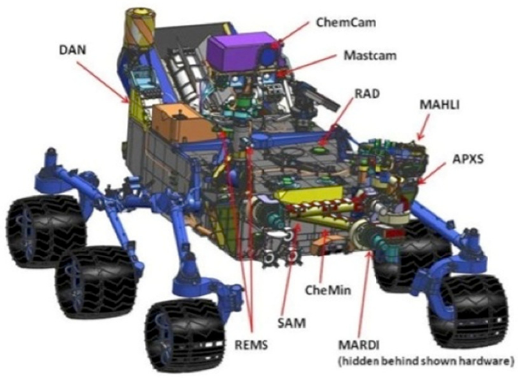

Figure 3. Instrument Mountings on the MSL Rover

LAUNCH PHASE

Overview

The launch vehicle is an Atlas V 541* EELV consisting of a liquid oxygen / kerosene Common Core Booster (CCB) first stage and a liquid oxygen / liquid hydrogen Centaur upper stage. The Launch phase begins when the spacecraft transfers to internal power on the launch pad and ends when the spacecraft has achieved a thermally stable, positive energy balance, commandable configuration, and has successfully played back the launch phase telemetry. After the initial ascent phase and following Main Engine Cutoff 1 (MECO1) of the Centaur upper state, the 165 km x 265 km, 28.9 deg inclination parking orbit is established. After the necessary coasting time in order to achieve the required departure geometry, the second Centaur burn injects the spacecraft onto the interplanetary transfer trajectory. Figure 4 shows the ascent profile and an exploded view of the Atlas V 541 launch vehicle.

Launch/Arrival Strategy Requirements

Delivering the next mobile science laboratory safely to the surface of Mars has various key challenges derived from a strict set of requirements which include launch vehicle performance, spacecraft mass, communications coverage during EDL, atmospheric-relative entry speed, latitude accessibility, and dust storm season avoidance.[1]

Launch phase mission requirements/constraints.

- Minimum 20-day launch period in the 2011 Earth to Mars opportunity.

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* Atlas family nomenclature: “5” denotes a 5-m payload fairing, “4” denotes four strap-on Solid Rocket Boosters (SRB), and “1” denotes a single-engine Centaur.

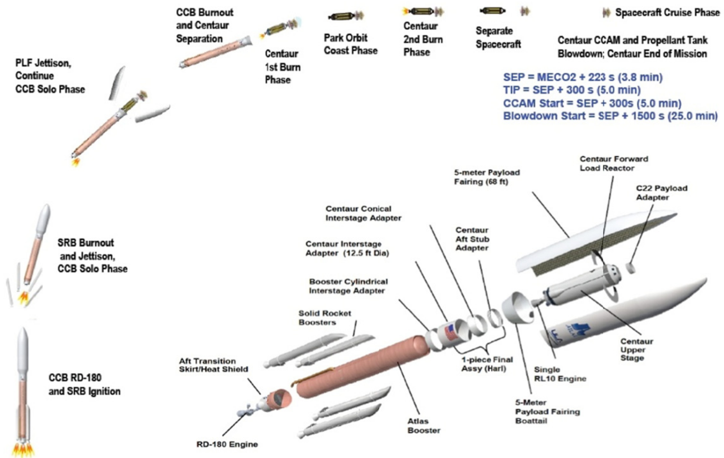

Figure 4. Atlas V 541 Ascent Profile and Exploded View

- Launch energy (C_3) less than 20.1 km^2/s^2, which corresponds to a maximum spacecraft injected mass of 4,050 kg on an Atlas V 541.
- Time from launch to spacecraft separation less than 101.5 min.
- Launch during daylight (requirement due to launching a payload with an MMRTG on board).

Arrival phase mission requirements/constraints.

- Atmosphere-relative entry speed between 5.3 km/s and 5.9 km/s.
- Longitude of the Sun at arrival (Ls) less than 170 deg.
- Accessibility to a range of landing latitudes that encompass the location of the current candidate landing sites, i.e. from 25°N to 27°S.

EDL coverage requirements/constraints.

- Full Entry, Descent and Landing (EDL) communications coverage (from atmospheric entry, defined to occur at a radius of 3522.2 km, through landing plus 1 min) via at least two of the following assets: Direct-To-Earth (DTE) using an X-band link, Mars Reconnaissance Orbiter (MRO) and Mars Odyssey (ODY) using an UHF link. MRO coverage always has priority over ODY coverage.
- MRO/ODY antenna angles (defined as the angle between the MSL anti-velocity vector and the direction to MRO/ODY) ≤ 135 deg during the EDL phase.
- DTE antenna angles (defined as the angle between the MSL anti-velocity vector and the direction to Earth) ≤ 75 deg during the EDL phase.
- Elevation of MRO/ODY/DTE at Landing and at Landing plus one min ≥ 10 deg.
- DTE EDL coverage from cruise stage separation to entry.

Several assumptions that mostly affected the feasibility of EDL coverage were also taken into account in order to determine the launch/arrival strategy:

- MRO's Local Mean Solar Time (LMST) node is nominally at 3:00 PM (ascending) and can be moved to provide EDL coverage to MSL.
- ODY's LMST node is nominally at 4:00 PM (descending) and can be moved to provide EDL coverage to MSL.

- Nominal atmospheric entry flight path angle (EFPA) = –15.5 deg (inertial)

The following guidelines were used as optimization criteria to determine the final launch/arrival strategy:

- Enable EDL coverage via Mars Odyssey.
    - In the few cases in which enough flexibility exists so that all mission constraints are satisfied and various solutions exist, EDL coverage via Mars Odyssey may be taken into account in the launch period selection, but may not compromise EDL coverage via MRO.
- Maintain MRO/ODY LMST nodes as close as possible to their nominal values.
    - Available MRO LMST nodes range between 3:00 PM and 1:45 PM. (LMST nodes at 1:30 PM may also be possible but have not been fully analyzed by the MRO flight team.)
    - Available ODY LMST nodes range between 4:00 PM and 3:00 PM.
- Minimize required number of target sets.
    - A target set is required when mission constraints cannot be satisfied simultaneously for all landing sites using the same launch/arrival dates. All target sets share the same launch days but may have different arrival dates.
- Provide as many launch days as possible.
- Keep arrival dates constant when possible.
    - Simplifies planning for surface mission operations.
- Keep antenna angles as low as possible to enable higher telecom margins during EDL.
- Arrive at Mars with Ls values as low as possible.

Due to the characteristics of the arrival geometries in the 2011 Earth to Mars opportunity and the flight dynamics of the spacecraft during descent, EDL coverage has these limitations:

- DTE coverage from entry to landing is not possible for all landing sites.
- Simultaneous UHF coverage via Mars Odyssey (ODY) is desired for redundancy but is not possible for all launch days for some landing sites.
- Dropouts in EDL communications are expected to occur between landing – 60 s and landing – 20 s due to parachute and powered descent dynamics.

Important navigation, trajectory correction maneuver, and orbit determination (OD) requirements related to planetary protection, cruise TCM ΔV and propellant requirements, and atmospheric entry delivery/knowledge accuracies are being satisfied but are not discussed in detail herein (see Cruise Section for additional details).

Launch Period

The three launch periods (referred to as Type 1A, Type 1B, and Type 1C) were developed to provide full MRO and ODY EDL communications coverage for landing latitudes between 25°N and 27°S. The launch periods differ primarily in terms of DTE communications coverage and the magnitude of change, if any, required for the orbiter LMST nodes. The Type 1A and Type 1B launch dates are bounded by atmosphere-relative entry speeds at the beginning of the launch period and by launch vehicle performance at the end of the launch period. The first launch day of the Type 1C launch period is the first launch day that meets the atmosphere-relative entry speed requirement and enables DTE coverage from entry to at least the end of the plasma attenuation period. The last launch day of the Type 1C launch period is bounded by launch vehicle performance. The arrival dates were selected based on the criteria described in the previous section.

The Type 1A and Type 1B launch periods extend from November 25 through December 18, 2011 and each has a single target set which covers landing latitudes from 25°N to 27°S. The Type 1A launch period provides full MRO EDL coverage and is optimized to maximize DTE coverage at the cost of moving the ODY LMST node as early as 3:00 PM for Southern landing sites. Full ODY EDL coverage for Southern landing sites is possible only for approximately the first half of the launch period. The Type 1A launch period provides full DTE coverage, or close to full DTE coverage, for the Northern landing site, but only partial DTE coverage for equatorial and Southern landing sites. Arrival dates for the Type 1A launch period extend from August 6 through August 20, 2012. A detailed description of the candidate landing sites is introduced in the Approach phase Section.

The Type 1B launch period is optimized to keep the orbiters as close as possible to their nominal LMST nodes at the time of arrival – i.e., MRO at ~3:00 PM and ODY at ~4:00 PM by reducing DTE coverage availability as necessary. For the Type 1B launch period, DTE coverage extends from entry to parachute deploy or longer for Northern and equatorial landing sites and from entry to the start of the plasma attenuation period for Southern landing sites. The Type 1B launch period has a constant arrival date of August 6, 2012.

Due to concerns regarding the lifetime of the MRO and ODY orbiters, a third launch/arrival strategy was developed in order to extend DTE coverage at least to the end of the plasma attenuation period across all landing sites while keeping both MRO and ODY as close as possible to their nominal LMST nodes. This launch period, known as the Type 1C launch period, is a variant of the Type 1A and Type 1B launch periods and extends from November 29 through December 18, 2011. The Type 1C launch period has a single target set which covers 25°N to 27°S with both MRO and ODY EDL coverage. For this strategy, MRO is not required to move from its nominal LMST node, whereas ODY would need to be moved as early as 3:15 PM for full EDL coverage at Southern landing sites. Arrival dates for the Type 1C launch period extend from August 8 through August 13, 2012.[4]

The Juno launch period extends from August 5 through August 27, 2011. Because Juno and MSL will launch on an Atlas V launch vehicle, they both will also use the same launch pad (LC-41). Since both launch periods are close in time, KSC has established an MSL Stay-Out zone that starts on September 6, 2011 and extends to the MSL launch period open. This MSL Stay-Out zone is required to refurbish the launch pad and complete pre-launch activities prior to the launch of MSL. Figure 5 shows the MSL and the Juno launch periods. Figure 6 shows the MSL launch/arrival strategy.

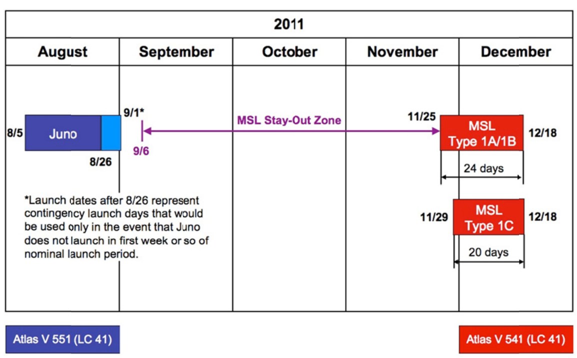

Figure 5. MSL and Juno Launch Periods

Launch Targets

The Earth-relative target conditions are specified by the injection energy per unit mass (C_3, or hyperbolic excess velocity squared, $C_3 = V_\infty^2$), the declination of the launch asymptote (DLA), and the right ascension of the launch asymptote (RLA) at the targeting interface point (TIP), defined as 5 min after spacecraft separation from the Centaur upper stage on a given launch date. Separation occurs 223 s after the Centaur second Main Engine Cutoff (MECO2). [1] These target conditions represent the conditions of the osculating departure hyperbola at TIP expressed in an Earth-centered, inertial, Earth Mean Equator and Equinox of Epoch J2000 (EME2000) coordinate system.

The injected spacecraft mass allocation is 4,050 kg, corresponding to a maximum C_3 of 20.1 km^2/s (assuming an instantaneous launch window). The maximum required C_3 is 20.1 km^2/s^2 (Type 1B) and occurs on the last day of the launch period. Tables 1 through 3 show the launch targets (C3, DLA, and RLA) and the atmosphere-relative entry speeds for each candidate landing site. The launch vehicle targets correspond to numerically integrated trajectories which are biased away from Mars in order to satisfy planetary protection requirements for the Centaur upper stage. Trajectory correction maneuvers (TCM) executed during cruise will be used to remove this biasing for launch vehicle dispersions, and target the selected landing site.

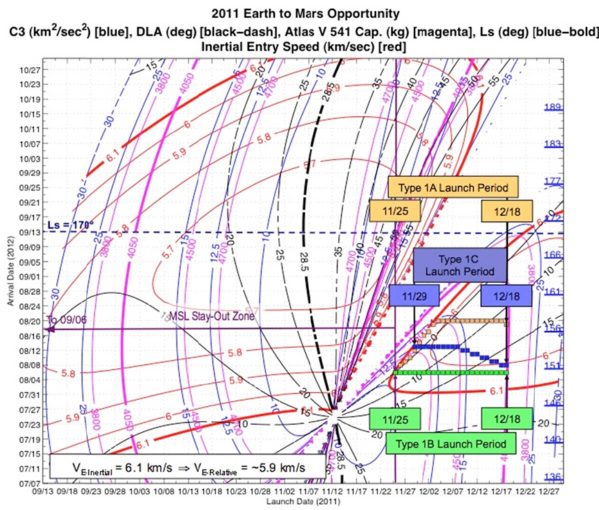

Figure 6. MSL Launch/Arrival Strategy

Table 1. Type 1A Launch Period Targets

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			Launch Targets Type 1A Launch Period EME2000 Coordinates^			Atmosphere-Relative Entry Speed^ (km/s)			
Launch Day	**Launch Date**	**Arrival Date**	**C3 (km2/s2)**	**DLA (deg)**	**RLA (deg)**	**Mawrth Vallis 2**	**Gale Crater**	**Eberswalde Crater**	**Holden Crater**
1	**11/25/2011**	**08/06/2012**	10.785	-0.738	126.596	5.884	5.865	5.881	5.886
2	**11/26/2011**	**08/08/2012**	11.365	-3.049	125.044	5.883	5.865	5.883	5.888
3	**11/27/2011**	**08/09/2012**	11.572	-2.524	124.433	5.868	5.850	5.868	5.873
4	**11/28/2011**	**08/10/2012**	11.805	-2.020	123.862	5.854	5.835	5.854	5.859
5	**11/29/2011**	**08/12/2012**	12.449	-3.884	122.645	5.856	5.838	5.859	5.864
6	**11/30/2011**	**08/14/2012**	13.159	-5.668	121.526	5.864	5.845	5.868	5.874
7	**12/01/2011**	**08/16/2012**	13.935	-7.375	120.498	5.875	5.857	5.882	5.888
8	**12/02/2011**	**08/17/2012**	14.152	-6.516	120.251	5.859	5.841	5.866	5.871
9	**12/03/2011**	**08/19/2012**	14.969	-8.050	119.391	5.874	5.856	5.883	5.889
10	**12/04/2011**	**08/20/2012**	15.195	-7.157	119.245	5.858	5.840	5.867	5.873
11	**12/05/2011**	**08/20/2012**	14.975	-4.273	119.650	5.818	5.800	5.825	5.830
12	**12/06/2011**	**08/20/2012**	14.941	-1.832	119.947	5.789	5.769	5.793	5.798
13	**12/07/2011**	**08/20/2012**	15.044	0.250	120.169	5.766	5.746	5.769	5.774
14	**12/08/2011**	**08/20/2012**	15.242	2.036	120.338	5.749	5.729	5.750	5.755
15	**12/09/2011**	**08/20/2012**	15.514	3.575	120.472	5.736	5.715	5.735	5.740
16	**12/10/2011**	**08/20/2012**	15.845	4.899	120.583	5.725	5.704	5.723	5.728
17	**12/11/2011**	**08/20/2012**	16.229	6.006	120.677	5.717	5.695	5.714	5.719
18	**12/12/2011**	**08/20/2012**	16.642	6.842	120.651	5.711	5.689	5.707	5.712
19	**12/13/2011**	**08/20/2012**	17.050	7.990	120.380	5.707	5.684	5.701	5.706
20	**12/14/2011**	**08/20/2012**	17.552	8.992	120.497	5.703	5.680	5.697	5.701
21	**12/15/2011**	**08/20/2012**	18.090	9.773	120.598	5.701	5.677	5.694	5.698
22	**12/16/2011**	**08/20/2012**	18.661	10.457	120.667	5.699	5.675	5.691	5.696
23	**12/17/2011**	**08/20/2012**	19.264	11.072	120.725	5.699	5.674	5.690	5.695
24	**12/18/2011**	**08/20/2012**	19.903	11.628	120.782	5.699	5.674	5.690	5.694
		MAX	19.903	11.628	126.596	5.884	5.865	5.883	5.889
		MIN	10.785	-8.403	119.245	5.699	5.674	5.690	5.694

Notes:
^ Maximum values across launch window.
- Biased, integrated launch targets based on Final Target Spec analysis

Table 2. Type 1B Launch Period Targets

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			Launch Targets Type 1B Launch Period EME2000 Coordinates^			Atmosphere-Relative Entry Speed^ (km/s)			
Launch Day	Launch Date	Arrival Date	C3 (km2/s2)	DLA (deg)	RLA (deg)	Mawrth Vallis 2	Gale Crater	Eberswalde Crater	Holden Crater
1	11/25/2011	08/06/2012	10.785	-1.116	126.596	5.884	5.865	5.881	5.886
2	11/26/2011	08/06/2012	10.721	1.954	126.616	5.862	5.843	5.858	5.862
3	11/27/2011	08/06/2012	10.780	4.116	126.515	5.848	5.828	5.841	5.846
4	11/28/2011	08/06/2012	10.921	5.886	126.331	5.837	5.816	5.829	5.834
5	11/29/2011	08/06/2012	11.118	7.359	126.094	5.829	5.808	5.820	5.825
6	11/30/2011	08/06/2012	11.360	8.603	125.826	5.824	5.802	5.814	5.818
7	12/01/2011	08/06/2012	11.637	9.667	125.543	5.819	5.797	5.809	5.813
8	12/02/2011	08/06/2012	11.946	10.586	125.255	5.816	5.794	5.805	5.809
9	12/03/2011	08/06/2012	12.283	11.387	124.969	5.814	5.791	5.801	5.806
10	12/04/2011	08/06/2012	12.646	12.092	124.691	5.812	5.789	5.799	5.803
11	12/05/2011	08/06/2012	13.032	12.714	124.424	5.810	5.787	5.797	5.802
12	12/06/2011	08/06/2012	13.441	13.268	124.173	5.810	5.786	5.796	5.800
13	12/07/2011	08/06/2012	13.872	13.762	123.938	5.809	5.786	5.795	5.799
14	12/08/2011	08/06/2012	14.325	14.205	123.723	5.809	5.785	5.795	5.799
15	12/09/2011	08/06/2012	14.800	14.600	123.532	5.809	5.785	5.794	5.798
16	12/10/2011	08/06/2012	15.300	14.949	123.373	5.809	5.785	5.794	5.798
17	12/11/2011	08/06/2012	15.830	15.232	123.279	5.810	5.786	5.795	5.799
18	12/12/2011	08/06/2012	16.433	15.158	123.457	5.811	5.786	5.795	5.799
19	12/13/2011	08/06/2012	16.820	15.957	122.210	5.812	5.787	5.796	5.800
20	12/14/2011	08/06/2012	17.451	16.224	122.377	5.813	5.788	5.797	5.801
21	12/15/2011	08/06/2012	18.077	16.449	122.339	5.814	5.789	5.798	5.802
22	12/16/2011	08/06/2012	18.725	16.660	122.266	5.816	5.791	5.799	5.803
23	12/17/2011	08/06/2012	19.401	16.856	122.193	5.818	5.793	5.801	5.805
24	12/18/2011	08/06/2012	20.108	17.037	122.129	5.820	5.794	5.803	5.807
		MAX	20.108	17.037	126.616	5.884	5.865	5.881	5.886
		MIN	10.721	-1.116	122.129	5.809	5.785	5.794	5.798

Notes:
^ Maximum values across launch window.
- Biased, integrated launch targets based on Final Target Spec analysis

Table 3. Type 1C Launch Period Targets

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			Launch Targets Type 1C Launch Period EME2000 Coordinates^			Atmosphere-Relative Entry Speed^ (km/s)			
Launch Day	Launch Date	Arrival Date	C3 (km2/s2)	DLA (deg)	RLA (deg)	Mawrth Vallis 2	Gale Crater	Eberswalde Crater	Holden Crater
1	11/29/2011	08/13/2012	12.951	-6.467	121.889	5.880	5.862	5.885	5.890
2	11/30/2011	08/13/2012	12.699	-3.263	122.214	5.842	5.824	5.845	5.850
3	12/01/2011	08/13/2012	12.639	-0.623	122.396	5.815	5.796	5.816	5.821
4	12/02/2011	08/13/2012	12.715	1.575	122.483	5.795	5.776	5.794	5.799
5	12/03/2011	08/13/2012	12.882	3.427	122.508	5.781	5.760	5.777	5.782
6	12/04/2011	08/13/2012	13.116	5.003	122.487	5.769	5.748	5.765	5.769
7	12/05/2011	08/13/2012	13.402	6.357	122.437	5.761	5.739	5.755	5.760
8	12/06/2011	08/13/2012	13.731	7.530	122.370	5.754	5.732	5.747	5.752
9	12/07/2011	08/13/2012	14.097	8.552	122.293	5.749	5.726	5.741	5.745
10	12/08/2011	08/13/2012	14.496	9.449	122.216	5.745	5.722	5.736	5.741
11	12/09/2011	08/12/2012	14.890	10.973	122.351	5.748	5.725	5.738	5.742
12	12/10/2011	08/12/2012	15.358	11.597	122.277	5.747	5.723	5.736	5.740
13	12/11/2011	08/11/2012	15.844	12.694	122.418	5.754	5.730	5.742	5.746
14	12/12/2011	08/11/2012	16.391	12.737	122.400	5.754	5.730	5.741	5.746
15	12/13/2011	08/10/2012	16.808	14.176	121.673	5.764	5.739	5.750	5.754
16	12/14/2011	08/10/2012	17.417	14.626	121.839	5.765	5.740	5.751	5.755
17	12/15/2011	08/09/2012	18.040	15.357	121.958	5.777	5.752	5.762	5.766
18	12/16/2011	08/09/2012	18.679	15.635	121.911	5.778	5.753	5.763	5.767
19	12/17/2011	08/08/2012	19.363	16.226	121.970	5.792	5.766	5.776	5.780
20	12/18/2011	08/08/2012	20.065	16.442	121.920	5.794	5.768	5.778	5.782
		MAX	20.065	16.442	122.508	5.880	5.862	5.885	5.890
		MIN	12.639	-6.861	121.673	5.745	5.722	5.736	5.740

Notes:
^ Maximum values across launch window.
- Biased, integrated launch targets based on Final Target Spec analysis

Excess launch vehicle performance with respect to the optimal launch time determines the duration of the daily launch window The launch window duration for all launch periods extends from close to two hours at the beginning of each of the launch periods to ~40 min at the end of the launch periods. Figure 7 shows the launch times for the three launch periods.

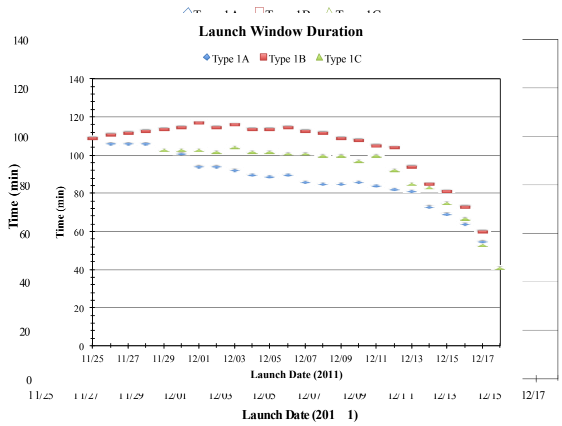


Figure 7. Launch Window Duration

To satisfy launch approval requirements when carrying an MMRTG, all launches must occur during daylight, which is defined to start at the beginning of morning civil twilight and end at the end of evening civil twilight.[3] Morning civil twilight is defined to begin when the geometric center of the Sun is 6° below the horizon prior to sunrise; likewise, evening civil twilight is defined to end when the geometric center of the Sun is 6° below the horizon after sunset. This requirement is met by launching the spacecraft on a short coast trajectory. Coast times, times from MECO1 and MES2 range from 11 min to 31 min. Launch times for the three launch periods are shown in Figure 8.

Spacecraft Separation Attitude

A spacecraft separation attitude has been determined to provide adequate telecom and power margins for the spacecraft following separation by satisfying the following angular requirements[4]: (1) The angle between the spacecraft –Z-axis and the Sun must not exceed 67 deg from separation to separation plus 15 days, (2) the angle between the spacecraft –Z-axis and each tracking station at station first rise must not exceed 79 deg, and (3) the angle between the spacecraft –Z-axis and Earth must not exceed 69 deg from separation plus 6 hours to separation plus 15 days. The selected spacecraft separation attitude for the spacecraft –Z-axis (same as Centaur –XB axis) in the EME2000 coordinate systems is as follows:

Declination:	12.00 deg
Right Ascension:	243.50 deg

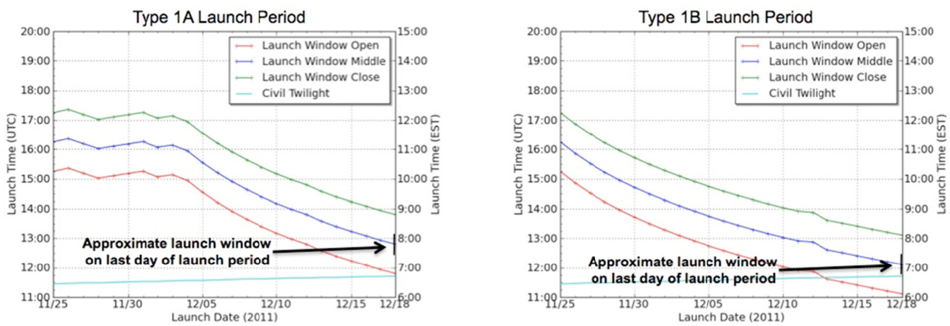
Initial Acquisition

Prior to separation from the launch vehicle, telemetry data from the MSL spacecraft will be transmitted to ground stations through the Centaur upper stage, which downlinks the data using the S-band telemetry system via the Tracking and Data Relay Satellite System (TDRSS). Once the spacecraft has separated from the Centaur, the goal is to establish a two-way coherent communication link via the Deep Space Network (DSN) within one hour of separation to generate orbit determination solutions that are used to deliver trajectory predicts for the second DSN pass. DSN initial acquisition always occurs at Canberra; however, a tracking gap between spacecraft separation and DSN station rise exists. This gap has two main components: a spacecraft transmission delay of six minutes after separation and a tracking coverage gap which may be as long as 20 min from separation to DSN station rise. In order to close this tracking gap, Perth and

New Norcia (ESA), Dongara (USN), and Mauritius (ISRO) tracking stations will be listening for the space-craft signal and record data in open loop[5].

On-Orbit Contingency Plan

In the scenario in which the Centaur upper stage fails to execute the second Centaur burn (MES2) so that the spacecraft is left in Earth parking orbit after MSL has been already separated, the project plans to execute what is referred to as the On-Orbit Contingency Plan (OOCP) to safely de-orbit the vehicle into the Pacific Ocean. In this case, the Dongara and South Point tracking stations would be used to command the vehicle, since no DSN ground stations would be able to transmit to the spacecraft while in low-Earth orbit.



Actual launch window duration depends on the launch vehicle performance achievable given the required C3 across a launch day.

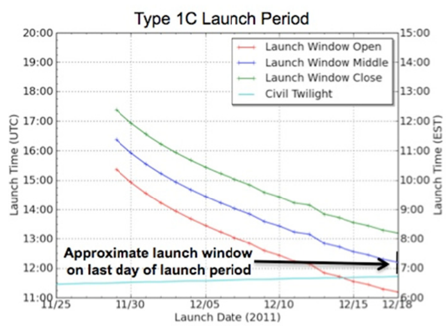


Figure 8. MSL Launch Times

CRUISE PHASE

Overview

The interplanetary Cruise phase starts after the end of the Launch phase once playback of the launch telemetry has been completed. Operationally, the Cruise phase begins with the first commanding of the spacecraft, a No-Op (no operational function) command following initial acquisition. Cruise ends and Approach begins when the spacecraft is 45 days from atmospheric entry.[1,2] The minimum and maximum combined Cruise and Approach phase duration is 232 days and 260 days respectively across the three launch periods. The Earth range at arrival is between 1.66 and 1.75 AU. The Sun range at arrival is between 1.52 and 1.54 AU. Primary activities during interplanetary cruise include Trajectory Correction Maneuvers (TCMs) to target the selected landing site, spacecraft and payload checkout and calibration, daily monitoring of spacecraft subsystems, and periodic attitude adjustments for power and telecommunications. The interplanetary transfer trajectories for the open (Nov 25, 2011) and close (Dec 18, 2011) of the Type 1B launch period are shown in Figure 9.

Cruise Trajectory Design

During interplanetary cruise, the spacecraft is spin-stabilized at 2 rpm. Up to six TCMs are planned to control the trajectory and adjust the atmospheric entry aimpoint, where the atmospheric entry interface point (EIP) is defined to be at a Mars radius of 3522.2 km. The first three TCMs occur during the Cruise phase and the final three occur during the approach phase. The locations of the six planned TCMs are also shown in Figure 9. Note that TCM-5X and TCM-6 are contingency maneuvers.[1,6]

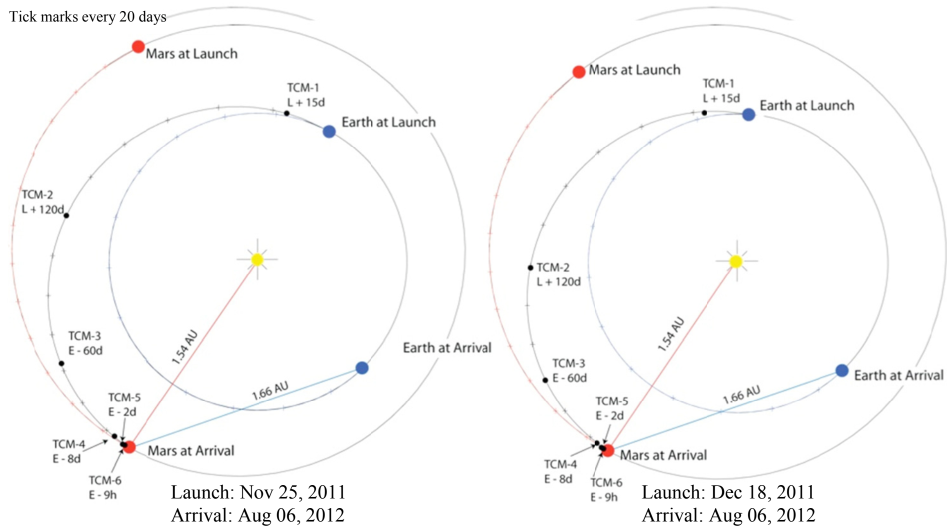


Figure 9. Interplanetary Trajectory for Open and Close of Type 1B Launch Period

The launch vehicle injects the spacecraft on an interplanetary trajectory targeted to an aimpoint that is biased away from Mars for planetary protection in order to achieve a probability less than 10^{-4} of the Centaur upper stage impacting Mars. In addition, planetary protection requires that the probability of an anomalous impact of the MSL spacecraft with Mars must be less than 10^{-2}. This is referred to as the non-nominal impact probability requirement. In order to satisfy the non-nominal impact probability requirement, the aimpoints for TCM-1 and TCM-2 must be biased away from Mars in order to reduce the time when a spacecraft failure would result in a non-nominal impact. Thus, TCM-3 is the first maneuver to target to the desired Mars atmospheric entry aimpoint. In addition, periodic attitude maintenance turns are performed to maintain adequate power and telecom margins, engineering and instrument checkouts and calibrations of various spacecraft systems are carried out.[1,6,7]

APPROACH PHASE

Overview

The Approach phase is defined to begin at 45 days prior to atmospheric entry (E-45 days) and ends when the spacecraft reaches the Mars atmospheric entry point. This mission phase is focused on preparations for Entry, Descent, and Landing (EDL) to ensure an accurate delivery to the required entry aimpoint and that all EDL sequence parameters are properly loaded on the spacecraft. Also, during this phase all activities that could compromise the spacecraft trajectory are minimized, and significant increases in DSN coverage and navigation tracking data are used to improve the accuracy of trajectory solutions for TCMs 4, 5, 5X, and 6. Preparations for EDL, which include initializing the onboard EDL flight software with the estimate of the atmospheric entry state vector, also occur during this phase.[7]

Approach Design & Geometry

The final navigation delivery accuracy at the atmospheric entry interface point is a function of the targeted landing site and the arrival date (determined by the launch date). Figure 10 shows the location of the four MSL candidate landing sites.[8] The MSL Project is scheduled to submit to NASA headquarters its final landing site recommendation in early July 2011. NASA headquarters is expected to make a decision on the final landing site by mid-July 2011. The performance of the telecommunications system just prior to, during, and after EDL is mainly driven by the geometry of the trajectory relative to Earth, as well as MRO and ODY. The Approach phase includes execution of TCM-4 and ends at the instant the spacecraft behavior transitions from Pre-EDL (PEDL) to EDL, nominally at Entry – 30 minutes. Figure 11 illustrates a typical arrival geometry showing MRO, Odyssey and Mars Express (MEX) providing EDL communications support to MSL.

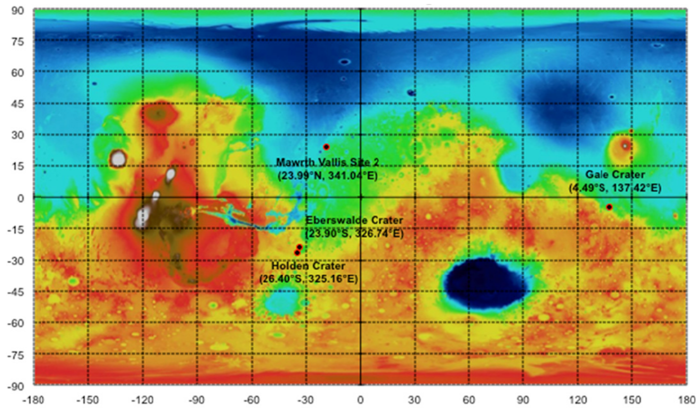


Figure 10. MSL Candidate Landing Sites

Approach Navigation

The radiometric data types that are used for MSL orbit determination during this phase are two-way coherent Doppler, two-way ranging, and ΔDOR measurements generated by the DSN X-band tracking system.[7]

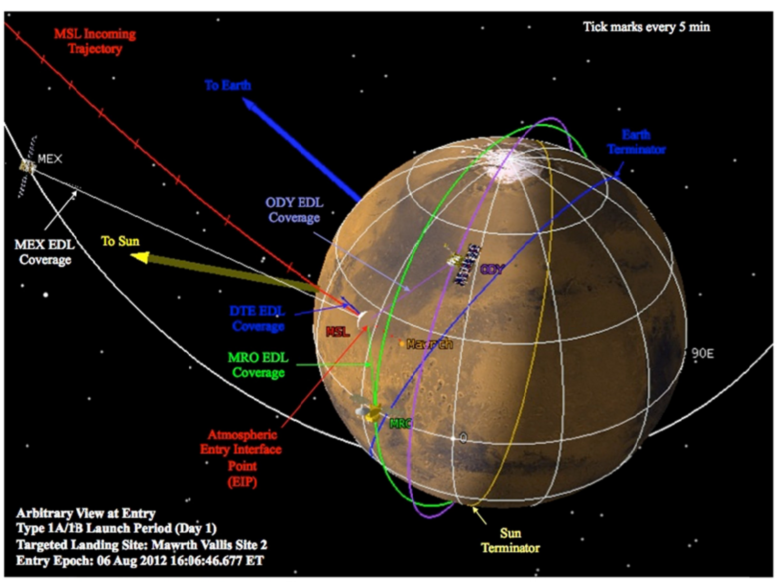


Figure 11. Arrival Geometry at Mawrth – Type 1A/1B Launch Period (Day 1)

TCM Delivery and Entry Knowledge Accuracies

In order to limit atmospheric entry dispersions to within the capabilities of the entry guidance system and to ensure flight system safety during EDL, the entry flight path angle delivery error must be less than ± 0.2 deg with respect to the targeted entry flight path angle. The entry state vector knowledge error at Entry – 9 minutes (based on a navigation data cutoff at Entry – 6 hours) must be less than 2.8 km in position and 2.0 m/s in velocity (all values quoted above are 3σ).[7]

ENTRY, DESCENT, AND LANDING PHASE

EDL Communications Coverage

The MSL launch/arrival strategy satisfies the requirement of maintaining full EDL communications from entry to landing plus one minute min via at least two assets. It is assumed that EDL communications are available when a direct line of sight between the orbiter (or Earth) and MSL exists, i.e., MSL is not being occulted by Mars as seen by the asset, and the antenna angle is within the antenna angle constraints. The antenna angle is defined as the angle between the atmosphere-relative anti-velocity vector and the line of sight to the asset. The antenna actually points along the -Z-axis, which is not necessarily oriented in the direction of the anti-velocity vector. However, comparisons of antenna angles measured with respect to the anti-velocity vector with those measured with respect to the -Z axis from 6 DOF simulations indicate that, for preliminary analysis, using the atmosphere-relative anti-velocity vector is a valid approximation.[8,9]

The X-band and UHF links are complimentary for EDL communications. Coverage of the entry phase favors X-band, since events during this phase are well spaced out in time, X-band is not sensitive to plasma attenuation effects, and MSL antenna angles are relatively low during this time. It is also likely that X-band could determine the cause of a failure from received tones; although, determining the precise conditions of the fault may not be possible. The powered descent phase favors the UHF link since a rapid succession of events occurs during this time, UHF antenna angles are low, and a significant amount of telemetry data are generated on board which is compatible with the data rates that the UHF relay is able to provide. This telemetry enables identification of most possible faults. Figures 12 and 13 show antenna angle histories for the UHF and X-bank links using different computation methods.

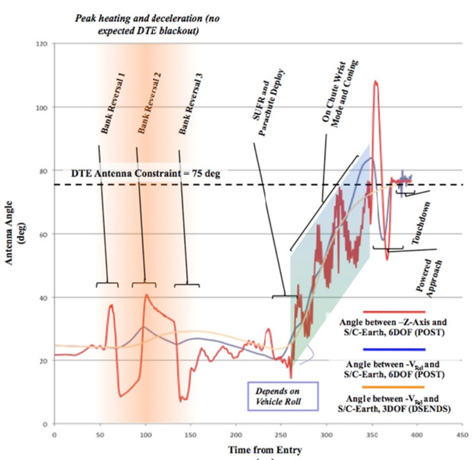


Figure 12. X-band Antenna Angle History

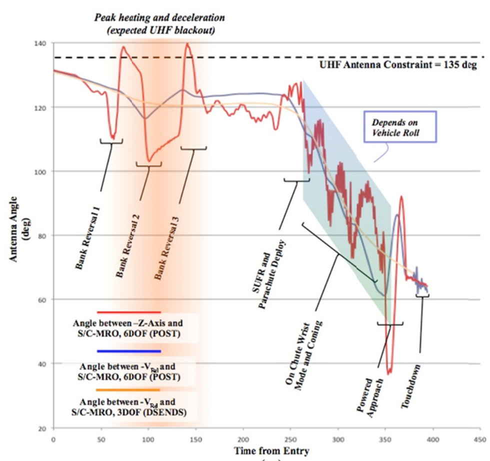


Figure 13. UHF Antenna Angle History

Additionally, it is required that the elevation angle at the time of landing and landing plus one minute must be at least 10 deg – i.e. the asset must be 10 deg or higher above the horizon between the time of landing and landing plus one minute.[10]

For any launch date and landing site, there is a range of relay orbiter LMST nodes that would place the orbit in the correct geometry in order to support EDL communications. The launch period design process evaluated the nominal nodes for both MRO (3:00 PM, ascending) and ODY (4:00 PM, descending) to determine whether the orbiters would have EDL communications coverage across all latitude bands for all launch days. When this goal could not be met, the latest LMST node (closest to the nominal) that would provide EDL coverage was determined. Keeping the LMST node of the orbiters as close as possible to their nominal values decreases the propellant usage of the orbiters, thereby potentially increasing their lifetimes and decreasing the impact on the orbiters' science return. Tables 4 through 7 show the latest required MRO and ODY nodes for the three launch periods along with DTE coverage availability.

Table 4. EDL Coverage for Type 1A Launch Period

<table>
<tr><th></th><th colspan="12">Type 1A Launch Period</th></tr>
<tr><th></th><th colspan="3">Mawrth Vallis Site 2 (23.99°N)</th><th colspan="3">Gale Crater (4.49°S)</th><th colspan="3">Eberswalde Crater (23.90°S)</th><th colspan="3">Holden Crater (26.40°S)</th></tr>
<tr><th></th><th>MRO</th><th>ODY</th><th>DTE</th><th>MRO</th><th>ODY</th><th>DTE</th><th>MRO</th><th>ODY</th><th>DTE</th><th>MRO</th><th>ODY</th><th>DTE</th></tr>
<tr><td>25-Nov-2011</td><td rowspan="6">3:00 PM</td><td rowspan="4">4:00 PM</td><td rowspan="5">Entry to ~Chute Deploy or Longer</td><td rowspan="10">3:00 PM</td><td>4:00 PM</td><td rowspan="24">Entry to ~Chute Deploy or Longer</td><td rowspan="20">3:00 PM</td><td>3:45 PM</td><td>^</td><td rowspan="21">3:00 PM</td><td>3:45 PM</td><td rowspan="3">Entry to ~Start of Plasma^^</td></tr>
<tr><td>26-Nov-2011</td><td rowspan="2">3:45 PM</td><td rowspan="2">3:35 PM</td><td rowspan="5">Entry to ~End of Plasma</td><td rowspan="2">3:35 PM</td></tr>
<tr><td>27-Nov-2011</td></tr>
<tr><td>28-Nov-2011</td><td>3:40 PM</td><td>3:30 PM</td><td>3:30 PM</td><td rowspan="4">Entry to ~End of Plasma or Longer</td></tr>
<tr><td>29-Nov-2011</td><td>3:55 PM</td><td>3:30 PM</td><td>3:20 PM</td><td>3:20 PM</td></tr>
<tr><td>30-Nov-2011</td><td>3:45 PM</td><td rowspan="19">Full EDL</td><td>3:20 PM</td><td>3:15 PM</td><td>3:15 PM</td></tr>
<tr><td>01-Dec-2011</td><td rowspan="2">2:55 PM</td><td rowspan="2">3:30 PM</td><td rowspan="2">3:05 PM</td><td>3:05 PM</td><td rowspan="18">Entry to ~Chute Deploy or Longer</td><td>3:05 PM</td></tr>
<tr><td>02-Dec-2011</td><td>3:00 PM</td><td>3:00 PM</td><td rowspan="17">Entry to ~Chute Deploy or Longer</td></tr>
<tr><td>03-Dec-2011</td><td>2:45 PM</td><td rowspan="2">3:15 PM</td><td rowspan="3">3:00 PM*</td><td>3:00 PM*</td><td rowspan="3">< 3:00 PM</td></tr>
<tr><td>04-Dec-2011</td><td>2:40 PM</td><td rowspan="2">< 3:00 PM</td></tr>
<tr><td>05-Dec-2011</td><td rowspan="8">2:45 PM</td><td>3:20 PM</td><td rowspan="4">2:55 PM</td></tr>
<tr><td>06-Dec-2011</td><td>3:25 PM</td><td rowspan="2">3:00 PM</td><td rowspan="13">3:00 PM*</td><td rowspan="13">3:00 PM*</td></tr>
<tr><td>07-Dec-2011</td><td rowspan="2">3:30 PM</td></tr>
<tr><td>08-Dec-2011</td><td rowspan="3">3:05 PM</td></tr>
<tr><td>09-Dec-2011</td><td rowspan="2">3:35 PM</td><td rowspan="3">2:50 PM</td></tr>
<tr><td>10-Dec-2011</td></tr>
<tr><td>11-Dec-2011</td><td rowspan="8">3:40 PM</td><td rowspan="8">3:10 PM</td></tr>
<tr><td>12-Dec-2011</td><td rowspan="3">2:45 PM</td></tr>
<tr><td>13-Dec-2011</td><td rowspan="4">2:40 PM</td></tr>
<tr><td>14-Dec-2011</td></tr>
<tr><td>15-Dec-2011</td><td rowspan="2">2:40 PM</td><td rowspan="2">2:55 PM</td></tr>
<tr><td>16-Dec-2011</td><td rowspan="3">2:55 PM</td></tr>
<tr><td>17-Dec-2011</td><td rowspan="2">2:35 PM</td><td rowspan="2">2:35 PM</td><td rowspan="2">2:50 PM</td></tr>
<tr><td>18-Dec-2011</td></tr>
</table>

*** Available Mean Anomaly range for full EDL coverage is less than orbiter's phasing control of +/- 1.6 deg**
^ Coverage extends from Entry to Entry + ~83 s (end of plasma is located at Entry + 90 s)
^^ For days 1, 2, and 3 coverage extends from Entry to Entry + ~77 s, ~83 s, and ~87 s respectively (end of plasma is located at Entry + 90 s)

Preliminary analysis shows that the most effective way for the orbiters to achieve the required LMST node is to execute a maneuver to change the orbit inclination that would start a nodal drift. Once the target LMST node has been achieved, another maneuver would be executed in order to stop the nodal drift. The more time that is allowed for the node to drift, the less propellant is required. Since the required LMST node is a function of launch day and landing site, the orbiter's nodal drift will not be started until after MSL launches.

Table 5. EDL Coverage for Type 1B Launch Period

<table>
<tr><th></th><th colspan="12">Type 1B Launch Period</th></tr>
<tr><th></th><th colspan="3">Mawrth Vallis Site 2
(23.99°N)</th><th colspan="3">Gale Crater
(4.49°S)</th><th colspan="3">Eberswalde Crater
(23.90°S)</th><th colspan="3">Holden Crater
(26.40°S)</th></tr>
<tr><th></th><th>MRO</th><th>ODY</th><th>DTE</th><th>MRO</th><th>ODY</th><th>DTE</th><th>MRO</th><th>ODY</th><th>DTE</th><th>MRO</th><th>ODY</th><th>DTE</th></tr>
<tr><td>25-Nov-2011</td><td rowspan="24">3:00 PM</td><td rowspan="24">4:00 PM</td><td rowspan="24">Entry to ~Chute Deploy or Longer</td><td rowspan="24">3:00 PM</td><td rowspan="23">4:00 PM</td><td rowspan="24">Entry to ~Chute Deploy or Longer</td><td rowspan="24">3:00 PM</td><td rowspan="2">3:45 PM</td><td rowspan="4">Entry to ~Start of Plasma^</td><td rowspan="24">3:00 PM</td><td rowspan="2">3:45 PM</td><td rowspan="9">Entry to ~Start of Plasma or Longer^^</td></tr>
<tr><td>26-Nov-2011</td></tr>
<tr><td>27-Nov-2011</td><td rowspan="14">3:50 PM</td><td rowspan="12">3:50 PM</td></tr>
<tr><td>28-Nov-2011</td></tr>
<tr><td>29-Nov-2011</td><td rowspan="20">Entry to ~End of Plasma or Longer</td></tr>
<tr><td>30-Nov-2011</td></tr>
<tr><td>01-Dec-2011</td></tr>
<tr><td>02-Dec-2011</td></tr>
<tr><td>03-Dec-2011</td></tr>
<tr><td>04-Dec-2011</td><td rowspan="15">Entry to ~End of Plasma or Longer</td></tr>
<tr><td>05-Dec-2011</td></tr>
<tr><td>06-Dec-2011</td></tr>
<tr><td>07-Dec-2011</td></tr>
<tr><td>08-Dec-2011</td></tr>
<tr><td>09-Dec-2011</td><td rowspan="5">3:45 PM</td></tr>
<tr><td>10-Dec-2011</td></tr>
<tr><td>11-Dec-2011</td><td rowspan="4">3:45 PM</td></tr>
<tr><td>12-Dec-2011</td></tr>
<tr><td>13-Dec-2011</td></tr>
<tr><td>14-Dec-2011</td><td rowspan="5">3:40 PM</td></tr>
<tr><td>15-Dec-2011</td><td rowspan="4">3:40 PM</td></tr>
<tr><td>16-Dec-2011</td></tr>
<tr><td>17-Dec-2011</td></tr>
<tr><td>18-Dec-2011</td><td>3:55 PM</td></tr>
</table>

^ For days 1, 2, 3, and 4, coverage extends from Entry to Entry + ~84 s, ~85 s, ~87 s, and ~89 s respectively (end of plasma is located at Entry + ~90 s)

^^ For days 1 through 8, coverage extends from Entry to Entry + ~78 s to ~89 s (end of plasma is located at Entry + ~90 s)

Table 6. EDL Coverage for Type 1C Launch Period

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<table>
<tr><th></th><th colspan="12">Type 1C Launch Period</th></tr>
<tr><th></th><th colspan="3">Mawrth Vallis Site 2
(23.99°N)</th><th colspan="3">Gale Crater
(4.49°S)</th><th colspan="3">Eberswalde Crater
(23.90°S)</th><th colspan="3">Holden Crater
(26.40°S)</th></tr>
<tr><th></th><th>MRO</th><th>ODY</th><th>DTE</th><th>MRO</th><th>ODY</th><th>DTE</th><th>MRO</th><th>ODY</th><th>DTE</th><th>MRO</th><th>ODY</th><th>DTE</th></tr>
<tr><td>25-Nov-2011</td><td rowspan="20">3:00 PM</td><td>3:45 PM</td><td>Full EDL</td><td rowspan="20">3:00 PM</td><td>3:20 PM</td><td rowspan="20">Entry to ~Chute Deploy or Longer</td><td rowspan="20">3:00 PM</td><td>3:15 PM</td><td rowspan="3">Entry to ~End of Plasma</td><td rowspan="20">3:00 PM</td><td>3:15 PM</td><td rowspan="8">Entry to ~End of Plasma or Longer</td></tr>
<tr><td>26-Nov-2011</td><td>3:55 PM</td><td rowspan="19">Entry to ~Chute Deploy or Longer</td><td>3:25 PM</td><td rowspan="3">3:20 PM</td><td rowspan="2">3:20 PM</td></tr>
<tr><td>27-Nov-2011</td><td rowspan="18">4:00 PM</td><td rowspan="2">3:30 PM</td></tr>
<tr><td>28-Nov-2011</td><td rowspan="3">Entry to End Guid</td><td rowspan="9">3:25 PM</td></tr>
<tr><td>29-Nov-2011</td><td>3:35 PM</td><td rowspan="6">3:25 PM</td></tr>
<tr><td>30-Nov-2011</td><td rowspan="5">3:40 PM</td></tr>
<tr><td>01-Dec-2011</td><td rowspan="14">Entry to ~Chute Deploy or Longer</td></tr>
<tr><td>02-Dec-2011</td></tr>
<tr><td>03-Dec-2011</td><td rowspan="12">Entry to ~End of Guided Entry or Longer</td></tr>
<tr><td>04-Dec-2011</td></tr>
<tr><td>05-Dec-2011</td><td rowspan="4">3:45 PM</td><td>3:30 PM</td></tr>
<tr><td>06-Dec-2011</td><td>3:25 PM</td></tr>
<tr><td>07-Dec-2011</td><td rowspan="4">3:30 PM</td><td rowspan="8">3:30 PM</td></tr>
<tr><td>08-Dec-2011</td></tr>
<tr><td>09-Dec-2011</td><td rowspan="6">3:50 PM</td></tr>
<tr><td>10-Dec-2011</td></tr>
<tr><td>11-Dec-2011</td><td rowspan="3">3:35 PM</td></tr>
<tr><td>12-Dec-2011</td></tr>
<tr><td>13-Dec-2011</td></tr>
<tr><td>14-Dec-2011</td><td>3:30 PM</td></tr>
</table>

In addition to the required LMST node, a range of mean anomalies at MSL entry for MRO and/or ODY must exist such that all the EDL coverage constraints mentioned earlier are satisfied. This range of mean anomalies defines the orbital phasings from which MRO or ODY could provide full EDL coverage. The committed phasing control for both MRO and ODY is ±30 s or ~±1.6 deg. Given this known uncertainty on the orbital phasing control of the orbiters, a valid mean anomaly range must not be less than 3.2 deg. Figure 14 shows EDL visibility for different mean anomaly phasings for launch at the open of the Type 1B launch period for the Mawrth landing site.[1, 10]

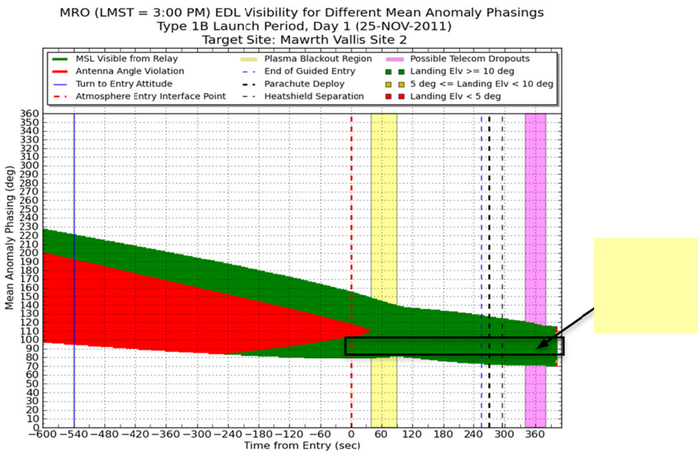

Figure 14. EDL Visibility for Different Mean Anomaly Phasings for MRO at 3:00 PM

EDL Events and Events Timeline

EDL Initialization.

EDL initialization is broken up into the final approach sub-segment and the EDL start sub-segment. The final approach sub-segment includes the final TCMs and EDL parameter and navigation updates. The final TCM opportunities include TCM-5 at E-2 days. There are other opportunities for contingency TCMs at E-1 day (TCM-5X) and E-9 hours (TCM-6) in case an emergency trajectory correction is needed. Final parameter and navigation update opportunities occur at E-1 day, E-9 hours and E-2 hours.

The EDL start sub-segment picks up at E-30 min and ends with issuance of the command for Cruise Stage Separation (CSS) at E-10 min. During this sub-segment, the X-band telecom is switched to tones (from being in lock with 500 bps telemetry). Also, the entry vehicle is thermally conditioned and the power system is reconfigured for EDL. The Heat-Rejection System (HRS) venting occurs at E-13.5 min.[9, 10, 11]

During final approach, the MSL EDL Instrumentation (MEDLI) suite on the heat shield is also enabled.

Exo-Atmospheric Segment.

Once the cruise stage separation command is sent, the Exo-atmospheric segment begins. Three major events occur during this segment:

1. Having issued the command at the conclusion of the previous segment, the cruise stage is mechanically separated from the entry vehicle.
2. Guidance, Navigation, and Control (GNC) is enabled at E-9 min. Once enabled, GNC will despin the entry body from its cruise spin rate of 2.5 rpm and turn the entry vehicle to the entry attitude.
3. The two 75-kg Cruise Balance Masses (CBMs) are separated, moving the center of mass of the entry body away from the centerline and inducing an angle of attack to enable aerodynamic lift.

The Exo-atmospheric segment ends with the spacecraft at the Entry interface, 3522.2 km from the center of Mars.

Entry Segment.

After the spacecraft reaches entry interface, the Entry segment begins. The major events that happen during this segment include:

1. The Reaction Control System (RCS) propulsion system required to achieve the desired control authority for bank reversals is pressurized.
2. Entry guidance becomes active, controlling the lift vector direction to achieve the desired downrange and cross range target.
3. Just prior to parachute deploy, the entry center of mass offset is eliminated by ejecting the six 25-kg Entry Balance Masses (EBMs). At the same time, the vehicle rolls to favorably point the Terminal Descent Sensor (TDS) toward the ground. This maneuver is known as the Straighten Up and Fly Right maneuver (SUFR) or ”Victory” Roll.

Peak aeroheating and deceleration are experienced during the Entry segment. Once flight conditions are within the supersonic parachute deploy envelope, the command for parachute deploy is issued, ending the Entry segment. This occurs at about E + 270 s. During EDL, the spacecraft transmits both DTE tones and UHF telemetry. Telecom performance for the received signal at Earth and/or relay assets depends upon the launch date and the selected landing site.

Parachute Descent Segment.

The parachute descent segment enables the spacecraft to prepare for powered descent and determine the time at which to initiate powered descent. The parachute descent segment begins with the execution of the parachute deployment trigger. Major events that occur during this segment include:

1. Parachute deployment (between Mach 1.8 and Mach 2.2) and full inflation about 2 s later.
2. Rate damping to eliminate wrist mode oscillations. The wrist mode management begins about 10 s after the parachute deploy trigger occurs.
3. Heat shield jettison occurring between Mach 0.5 and Mach 0.8. The jettison of the heat shield allows the Terminal Descent Sensor (TDS) to start acquiring data.
4. TDS surface acquisition begins providing altitude and velocity measurements to update the navigated state. Once altitude solutions are reached, surface relative navigation begins.
5. Mars Landing Engine (MLE) priming to allow fuel flow through MLEs.

The command to jettison the backshell and parachute occurs between 1.5 and 2.0 km above ground level and at a velocity near 100 m/s as measured by the TDS, which ends the parachute descent segment.

Powered Descent Segment.

The powered descent segment begins at backshell separation. During powered descent, propulsive control is provided by actuation of eight independently throttleable MLEs mounted on the descent stage. Four sub-segments in the powered descent sequence include:

1. Powered approach: Divert maneuver for backshell avoidance. This sub-segment also brings the Powered Descent Vehicle (PDV) to vertical flight at a descent rate of 20 m/s.
2. Constant velocity accordion: Adjusts for ±50 m altitude error at backshell separation.
3. Constant deceleration: Slows skycrane to a vertical velocity of 0.75 m/s for starting the sky crane segment. The descent stage maintains this vertical descent rate throughout the sky crane segment (except during the final 0.25 s when the descent stage slows to 0 m/s in preparation for flyaway).
4. Throttle down: Throttle down the four “inboard” MLEs to near shutdown (1%) while keeping the four remaining MLEs to function in the more efficient range of 50% throttle.

The powered descent segment ends at the command for rover separation from the descent stage.

Sky Crane Segment.

The sky crane segment begins when the command for rover separation is issued by the GNC mode commander. This occurs at an altitude of approximately 18.6 m. The events that occur in this segment include:

1. Rover is lowered on a Descent Rate Limiter (DRL) and Bridle Umbilical Device (BUD) combination to 7.5 m below the descent stage. A multi-conductor umbilical cable also connects the descent stage to the rover, allowing communication between the descent stage and rover computers and the use of the UHF antenna mounted on the descent stage.
2. Rover mobility system is deployed into the touchdown configuration while the rover is being lowered on the BUD.
3. Touchdown logic is enabled 9 s after the rover separates from the descent stage (still connected via the DRL and BUD).
4. The descent stage continues descent until a post-touchdown state is detected.

For touchdown detection, a check is made to determine if the commanded thrust profile is flat. If the thrust profile is sufficiently flat, then another check is made to determine if the mean throttle setting is below the prescribed touchdown threshold. Once this throttle down is detected and passes a persistence check, the descent stage computer instructs the rover to cut the DRL and BUD. The bridle cut command ends the sky crane segment.

Fly Away Segment.

After touchdown is declared, transition to flyaway begins. Flyaway is performed using the flyaway controller executing on the descent stage processor (SPARC) in the Descent Motor Control Assembly (DMCA) on the descent stage. The following events occur after touchdown is declared:

1. Descent stage slows down to 0 m/s.
2. Controlled transferred from Rover Compute Element (RCE) to DMCA.
3. Bridle and electrical umbilical are cut.

Once the bridle and electrical umbilical are cut, the flyaway controller exhibits three phases:

1. Hover – Used for the period of time required to cut the electrical umbilical between the rover and the descent stage.
2. Ascent – To maintain MLE plume ground pressure below landing pressure, the descent stage travels straight up.
3. Turn and Burn – Two of the MLE engines are brought to 100% while the other two engines are at slightly less than 100%, causing the descent stage to pitch about the descent stage Y-axis to 45°. Once the turn duration is complete, all four engines are brought to 100% with the controller making adjustments for maintaining zero attitude rates. Constant thrust is applied for enough time to ensure that the descent stage will impact the surface at least 150 m from the rover's position.

The flyaway segment and the EDL phase end when all flight system components have zero kinetic energy.

MSL Telecom System Description

Throughout the EDL phase, each telecom antenna is used with the exception of the X-band antennas (High Gain Antenna (HGA) and Rover Low Gain Antenna (RLGA)) on the rover. The EDL timeline commands transition between the antenna paths, and directs the system to switch data processing as needed to coordinate with those antenna transitions. Figure 15 identifies the locations of the antennas onboard the spacecraft.

EDL communications start with an initial configuration of direct-to-Earth (DTE) X-band telemetry at 500 bps via the Medium Gain Antenna (MGA). Prior to cruise stage separation, EDL communications transitions to X-band Multi Frequency Shift Key (MFSK) tones via the parachute low gain antenna (PLGA); the PLGA is from cruise stage separation to entry interface.[10]

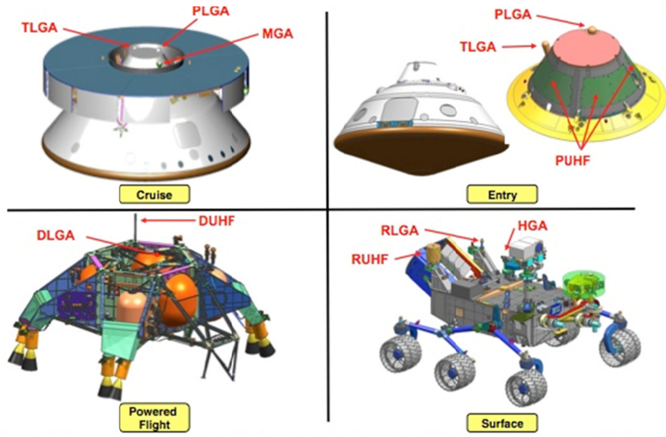

Figure 15. X-band and UHF Antenna Locations

After cruise stage separation, during Exo-atmospheric flight, the UHF path is brought online via the wraparound parachute UHF antenna (PUHF) in parallel with continued DTE X-band tones via the PLGA. At entry interface, the X-band transitions to the tilted low gain antenna (TLGA); the TLGA and PUHF are used through backshell separation. After backshell separation, the X-band link transitions to the Descent Stage low gain antenna (DLGA), and the UHF transitions to using the Descent Stage UHF (DUHF) antenna. The DLGA is used through all of powered flight and through the end of flyaway with the disposal of the descent stage and its associated hardware. The UHF link transitions from the DUHF to the Rover UHF antenna (RUHF) at rover separation from the descent stage, with the RUHF used through rover transition to surface nominal mode. Figure 16 shows the different antennas used during EDL.[9]

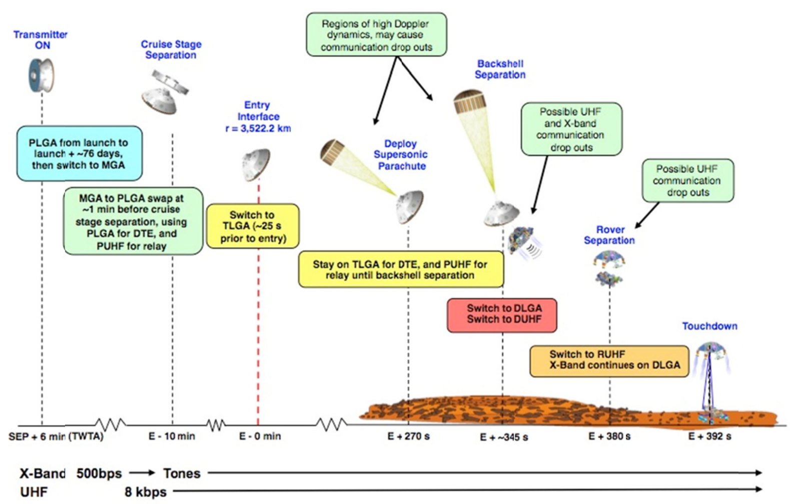

Figure 16. Antenna Utilization during EDL

CONCLUSIONS

This paper has summarized the final Mars Science Laboratory launch/arrival strategy and demonstrated that all mission design requirements and constraints can be achieved. The MSL launch/arrival strategy consists of two 24-day launch periods and one 20-day launch period that provide EDL communications for landing latitudes between 25°N and 27°S via at least two of the following assets: Direct-To-Earth (DTE) using an X-band link, Mars Reconnaissance Orbiter (MRO) and Mars Odyssey (ODY) using an UHF link.

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